Chapter 8: Oceans and Climate

Learning Objectives

After reading this chapter you should:

- understand the concept of the heat budget of the earth (you do not need to remember all of the percentages, just general trends)
- know the difference and relative importance of radiation, conduction and phase change in exchanging heat with the atmosphere
- understand the mechanisms and causes of the greenhouse effect and global warming
- understand how evaporation and condensation transport heat in the atmosphere and oceans
- understand how the curvature of the Earth results in differential heating of the surface
- understand the role played by albedo in radiation reaching the Earth
- understand how and why atmospheric convection cells form
- understand the reasons for and the results of the Coriolis Effect
- be able to derive the major wind patterns on Earth
- understand the relationship between climatic zones and convection cells – e.g. why are rainforests along the equator?
- understand the effects of altitude on air masses and climate
- understand how seasonal and daily cycles effect things like land and sea breezes
- understand how hurricanes form
- understand the potential impacts of climate change

The ultimate source of energy driving the motion of the atmosphere and the ocean is radiant energy from the sun, which falls on different parts of the Earth in differing amounts. The oceans are the recipient of most of this solar energy, and they are therefore a major factor in regulating Earth's climate.

Remember that compared to land temperatures, ocean temperatures do not undergo large swings from day to night or seasonally. This is due to a number of factors;

- Water has a very high heat capacity, so it can absorb a large amount of heat without much of an increase in temperature. Water can also release large amounts of heat back to the atmosphere without its temperature declining as much as land temperatures would.
- On land, the solar energy only hits the surface, which can heat up dramatically, but the heat does not penetrate very far below the surface. In water, light penetrates for a few hundred meters, so the heat is distributed through a greater area, and water does not heat up as quickly as land.
- Mixing of water in the top few hundred meters also distributes heat. Mixing does not happen on land.

Because of water's ability to regulate heat exchange and climate, areas near the oceans usually have a much milder climate than regions in the center of the continents. Furthermore, areas in the Southern Hemisphere have a much more moderate climate than regions of similar latitude in the Northern Hemisphere, because a larger proportion of the Southern Hemisphere is covered by oceans.

8.1 Earth's Heat Budget

The balance of incoming and outgoing heat on Earth is referred to as its **heat budget**. As with any budget, to maintain constant conditions the budget must be balanced so that the incoming heat equals the outgoing heat. The heat budget of Earth appears below (Figure 8.1.1).

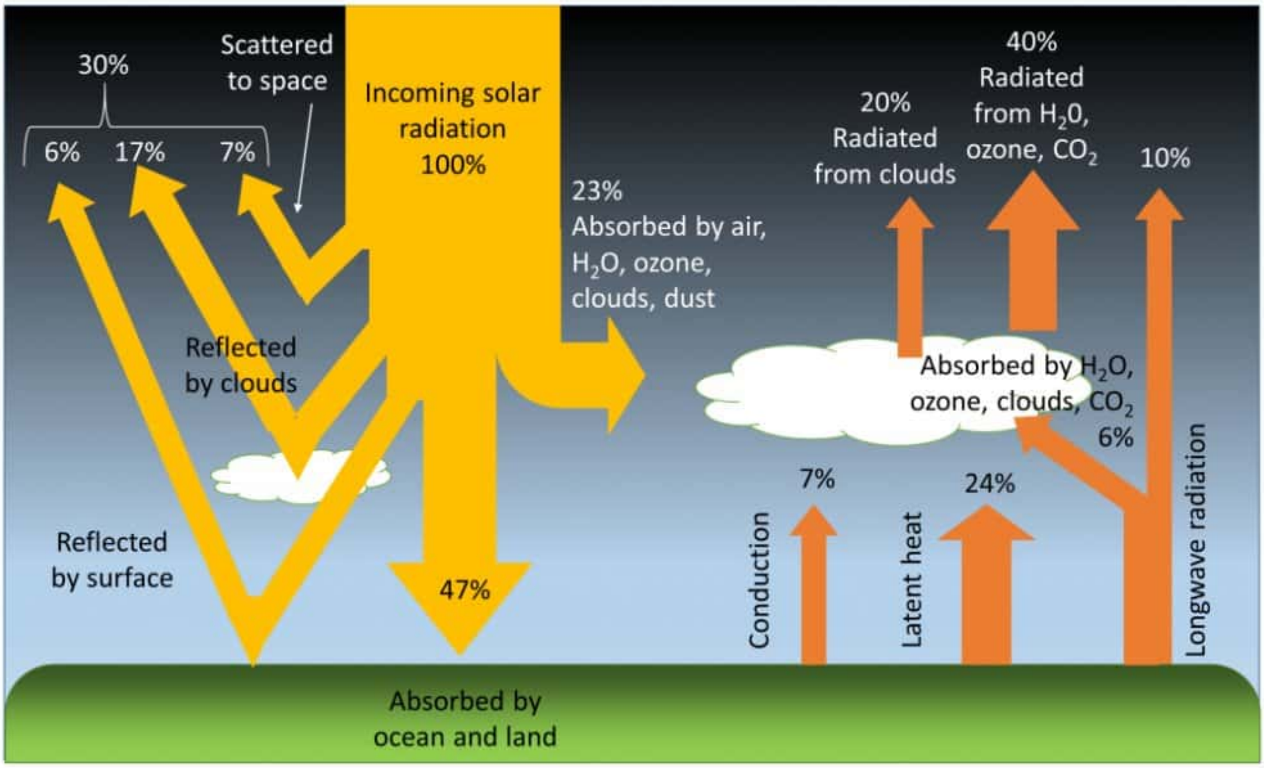


Figure 8.1.1 *Earth's heat budget. Of all of the solar radiation reaching Earth, 30% is reflected back to space and 70% is absorbed by the Earth (47%) and atmosphere (23%). The heat absorbed by the land and oceans is exchanged with the atmosphere through conduction, radiation, and latent heat (phase change). The heat absorbed by the atmosphere is eventually radiated back into space (PW).*

Of all of the solar energy reaching the Earth, about 30% is reflected back into space from the atmosphere, clouds, and surface of the Earth. Another 23% of the energy is absorbed by the water vapor, clouds, and dust in the atmosphere, where it is converted into heat. Just under half (47%) of the incoming solar radiation is absorbed by the land and ocean, and this energy heats up the Earth's surface. The energy absorbed by the Earth returns to the atmosphere through three processes; conduction, radiation, and latent heat (phase change)(Figure 8.1.1).

Conduction is the transfer of heat through direct contact between the surface and the atmosphere. Air is a relatively poor thermal conductor (which means it is a good insulator), so conduction represents only a small part of the energy transfer between the Earth and the atmosphere; equal to about 7% of the incoming solar energy.

All bodies with a temperature above absolute zero (-273° C) radiate heat in the form of longwave, infrared **radiation** (see the electromagnetic spectrum in section 6.5). The warmed Earth is no exception, and about 16%

of the original solar energy is radiated from the Earth to the atmosphere (Figure 8.1.1). Some of this radiated energy will dissipate into space, but a significant amount of heat will be absorbed by the atmosphere. This is the basis for the **greenhouse effect** (Figure 8.12). In the greenhouse effect, shortwave solar radiation passes through the atmosphere and reaches the Earth's surface where it gets absorbed. When the radiation is re-emitted by the Earth, it is now in the form of long wavelength, infrared radiation, which does not easily pass through the atmosphere. Instead, this infrared radiation is absorbed by the atmosphere, particularly by the greenhouse gases such as CO_2, methane, and water vapor. As a result, the atmosphere heats up. Without the greenhouse effect, the average temperature on Earth would be about -18° C, which is too cold for liquid water, and therefore life as we know it could not exist!

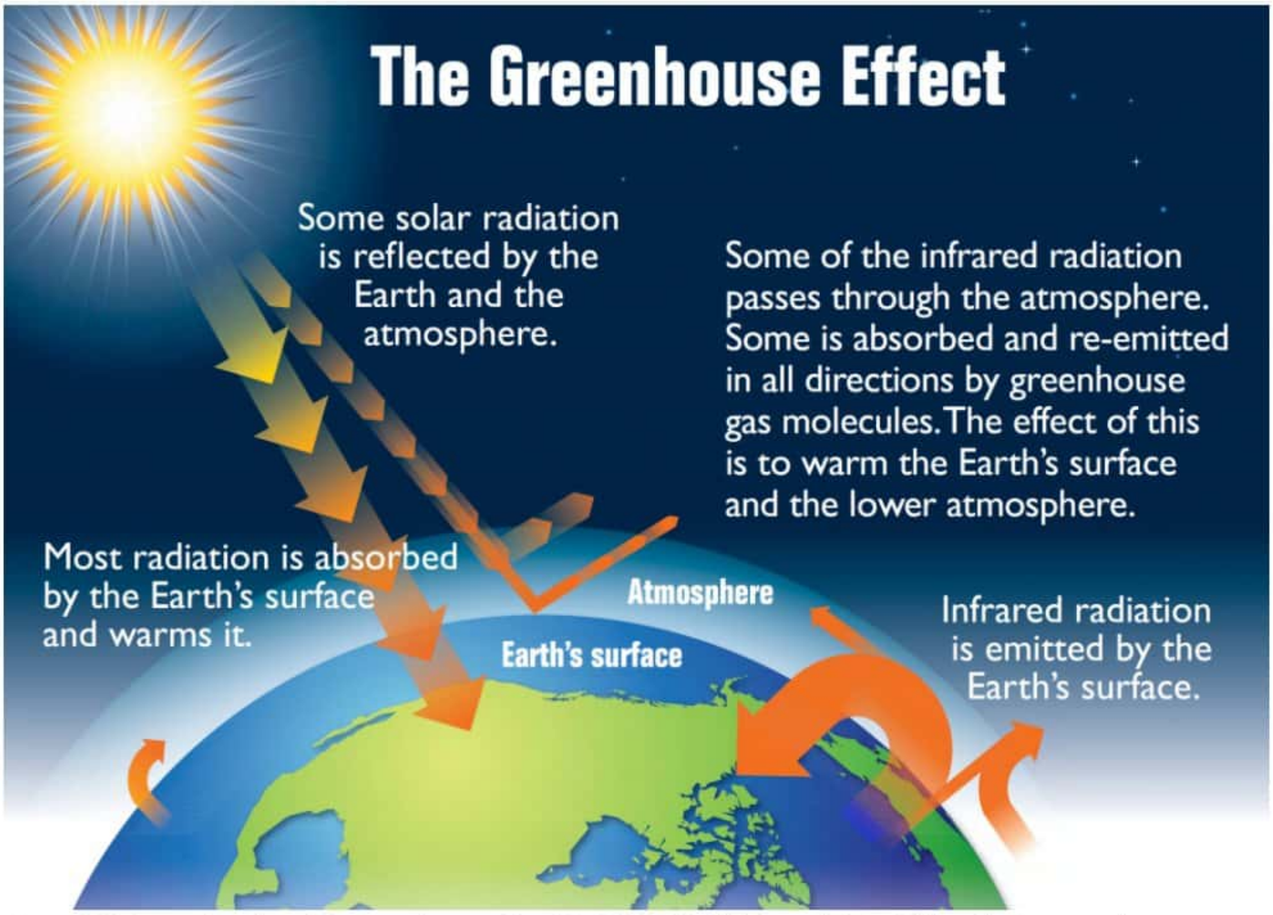


Figure 8.1.2 *An explanation of the greenhouse effect (By US EPA [Public domain], via Wikimedia Commons).*

There is a great deal of concern about the greenhouse effect across the globe; not because of the presence of the effect itself, but because the effect is intensifying, causing climate change or global warming. Since the Industrial Revolution the atmospheric concentrations of the major greenhouse gases, particularly CO_2 and methane, have increased dramatically due to industrialization, the burning of fossil fuels, and deforestation. At the same time, there has been rapid warming of the global climate; CO_2 concentrations have increased more than 25% and global temperature has risen by 0.5° C over the past century. Unless production of these greenhouse gases is curbed, this rapid warming trend may continue, with potentially dire consequences. See section 8.5 for detailed information on the causes and effects of climate change.

The largest pathway for heat exchange between the land or oceans and the atmosphere is **latent heat** transferred through **phase changes**; heat released or absorbed when water moves between solid, liquid, and vapor forms (see section 5.1). Heat must be added to liquid water to make it evaporate, and when water vapor is formed, that heat is removed from the ocean and transferred to the atmosphere along with the water vapor. When water vapor condenses into rain, that heat is then returned to the oceans. The same process happens with the formation and melting of ice. Heat is absorbed by ice when it melts, and heat is released when ice forms, and these phase changes transfer heat between the oceans and the atmosphere.

To complete the heat budget, the heat that is absorbed by the atmosphere either directly from solar radiation or as a result of conduction, radiation and latent heat, is eventually radiated back into space (Figure 8.1.1).

Differential Heating of Earth's Surface

If the Earth was a flat surface facing the sun, every part of that surface would receive the same amount of incoming solar radiation. However, because the Earth is a sphere, sunlight is not equally distributed over the Earth's surface, so different regions of Earth will be heated to different degrees. This differential heating of Earth's surface occurs for a number of reasons. First, because of the curvature of Earth, sunlight only falls perpendicularly to the surface at the center of the sphere (equatorial regions). At any other point on Earth, the angle between the surface and the incoming solar radiation is less than 90°. Because of this, the same amount of incoming solar radiation will be concentrated in a smaller area at the equator, but will be spread over a much larger area at the poles (Figure 8.1.3). Thus the tropics receive more intense sunlight and a greater amount of heating per unit of area than the polar regions.

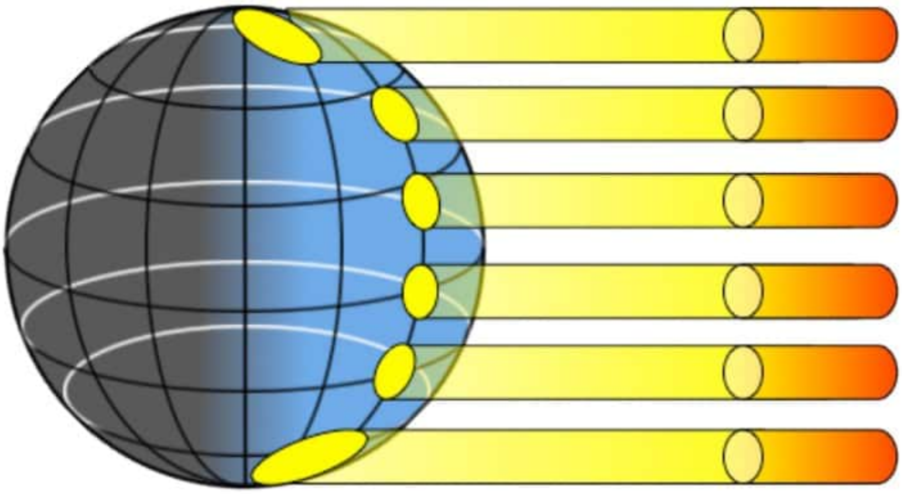


***Figure 8.1.3** Because of the curvature of the Earth, the same amount of sunlight will be spread out over a larger area at the poles compared to the equator. The equator therefore receives more intense sunlight, and a greater amount of heat per unit of area (By Thebiologyprimer (Own work) [CC0], via Wikimedia Commons).*

The angle at which sunlight strikes the Earth contributes to differential heating of the surface in an additional way. At the poles, because of the angle at which the solar energy strikes the surface, more of the light will glance off of the surface and the atmosphere and be reflected back into space. At the equator, the direct angle with which light reaches the surface results in more of the energy being absorbed rather than reflected. Finally, the poles reflect more solar energy than other parts of the Earth because the poles have a higher **albedo**. The albedo refers to reflectivity of a surface. Lighter surfaces are more reflective than darker surfaces (which absorb more energy), and therefore have a higher albedo. At the poles, the ice, snow and cloud cover create a much higher albedo, and the poles reflect more and absorb less solar energy than the lower latitudes. Through all of these mechanisms, the poles absorb much less solar radiation than equatorial regions, which is why the poles are cold and the tropics are very warm.

But there is an interesting twist to this global distribution of heat. The tropical regions actually receive more radiant heat than they emit, and the poles emit more heat than they receive (Figure 8.1.4). We should therefore expect that the tropics will be getting continually warmer, while the poles become increasingly cold. Yet this is not the case; so what is happening? Rather than the heat remaining isolated near the equator, about 20% of the heat from the tropics is transported to the poles before it is emitted. This large scale transport of energy moderates the climates at both extremes. The mechanisms for this heat transfer are ocean and atmospheric circulation, the topic of the next section.

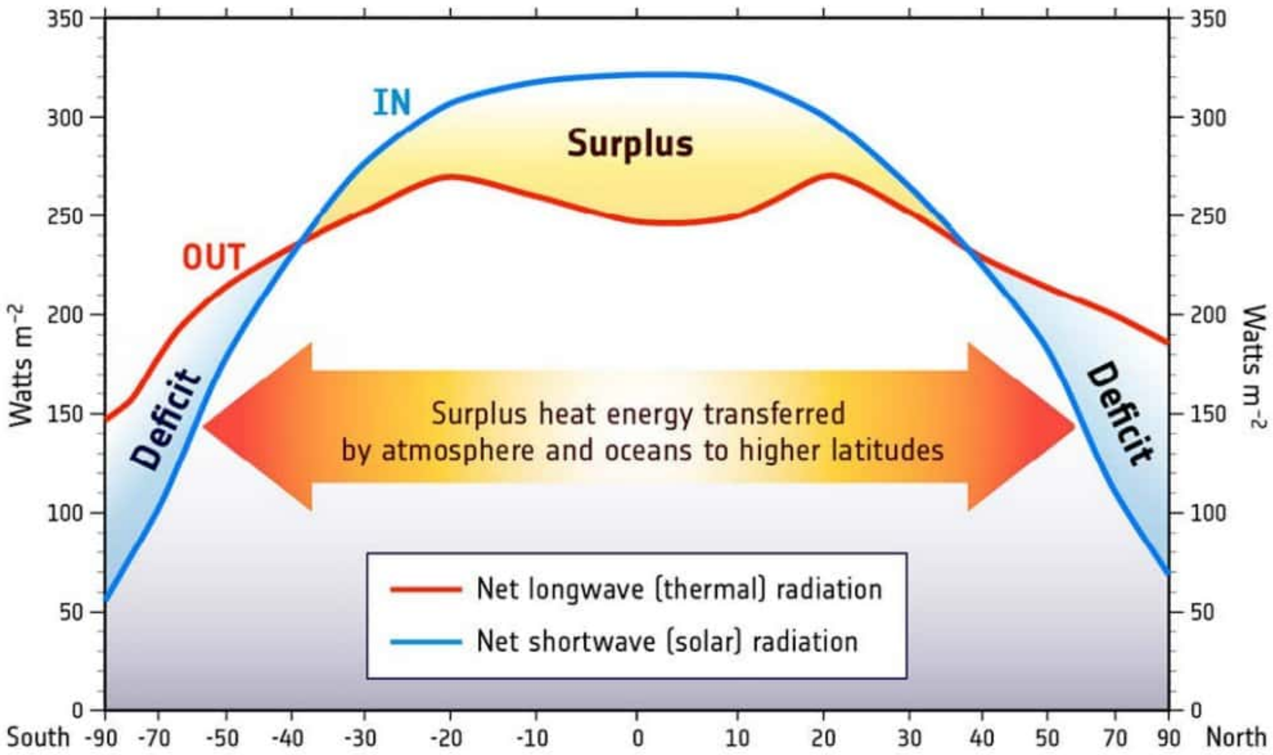


Figure 8.1.4 *The balance between heat gain and heat loss as a function of latitude. Excess heat received near the equator is transferred towards the poles (National Oceanography Centre (NOC). Creative Commons 3.0 unported license).*

The idea of differential heating of the Earth's surface is fundamental to understanding a wide range of oceanographic and atmospheric processes. This differential heating leads to atmospheric convection, which creates winds, which blow over the water and create waves and surface currents, and these currents influence nutrient distribution, which promotes primary production, which then supports the rest of the ocean ecosystem. So there's a lot riding on the simple fact that more light reaches the tropics than the poles!

8.2 Winds and the Coriolis Effect

Differential heating of the Earth's surface results in equatorial regions receiving more heat than the poles (section 8.1). As air is warmed at the equator it becomes less dense and rises, while at the poles the cold air is denser and sinks. If the Earth was non-rotating, the warm air rising at the equator would reach the upper atmosphere and begin moving horizontally towards the poles. As the air reached the poles it would cool and sink, and would move over the surface of Earth back towards the equator. This would result in one large atmospheric convection cell in each hemisphere (Figure 8.2.1), with air rising at the equator and sinking at the poles, and the movement of air over the Earth's surface creating the winds. On this non-rotating Earth, the prevailing winds would thus blow from the poles towards the equator in both hemispheres (Figure 8.2.1).

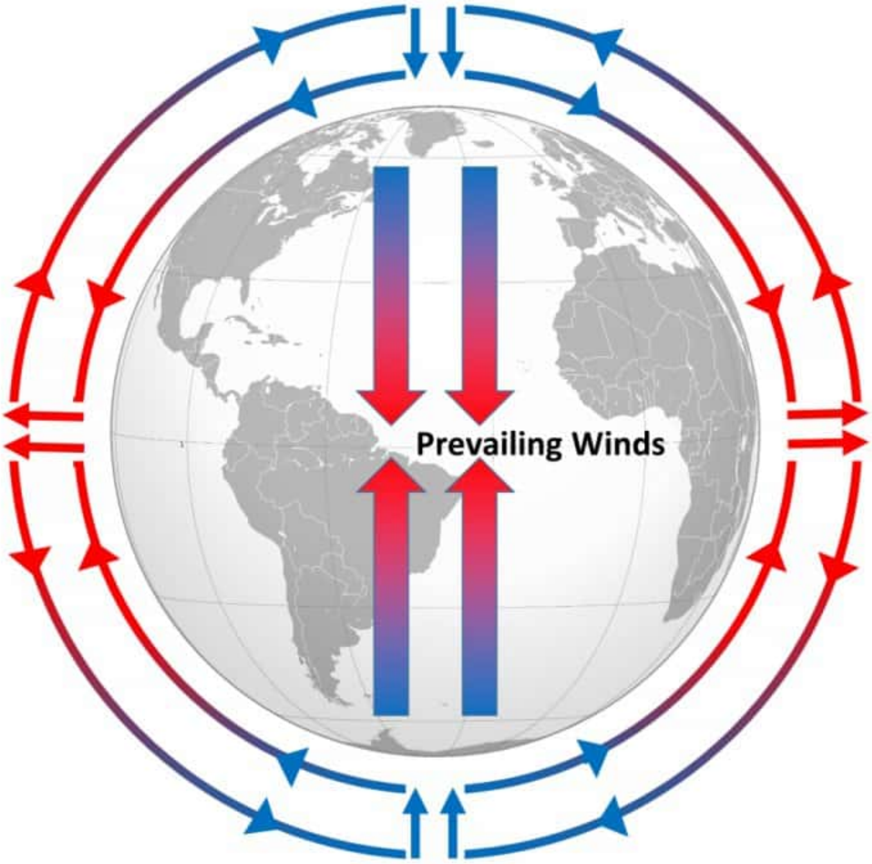


Figure 8.2.1 *Hypothetical atmospheric convection cells on a non-rotating Earth. Air rises at the equator and sinks at the poles, creating a single convection cell in each hemisphere. The prevailing winds moving over the Earth's surface blow from the poles towards the equator in both hemispheres (Modified by PW from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).*

The non-rotating situation in Figure 8.2.1 is of course only hypothetical, and in reality the Earth's rotation makes this atmospheric circulation a bit more complex. The paths of the winds on a rotating Earth are deflected by the **Coriolis Effect**. The Coriolis Effect is a result of the fact that different latitudes on Earth rotate at different speeds. This is because every point on Earth must make a complete rotation in 24 hours, but some points must travel farther, and therefore faster, to complete the rotation in the same amount of time. In 24 hours a point on the equator must complete a rotation distance equal to the circumference of the Earth, which is about 40,000 km. A point right on the poles covers no distance in that time; it just turns in a circle. So the speed of rotation at the equator is about 1600 km/hr, while at the poles the speed is 0 km/hr. Latitudes in between rotate at intermediate speeds; approximately 1400 km/hr at 30^o and 800 km/hr at 60^o. As objects move over the surface of the Earth they encounter regions of varying speed, which causes their path to be deflected by the Coriolis Effect.

To explain the Coriolis Effect, imagine a cannon positioned at the equator and facing north. Even though the cannon appears stationary to someone on Earth, it is in fact moving east at about 1600 km/hr due to Earth's rotation. When the cannon fires the projectile travels north towards its target; but it also continues to move to the east at 1600 km/hr, the speed it had while it was still in the cannon. As the shell moves over higher latitudes, its momentum carries it eastward faster than the speed at which the ground beneath it is rotating. For example, by 30^o latitude the shell is moving east at 1600 km/hr while the ground is moving east at only 1400 km/hr. Therefore, the shell gets "ahead" of its target, and will land to the east of its intended destination. From the point of view of the cannon, the path of the projectile appears to have been deflected to the right (red arrow, Figure 8.2.2). Similarly, a cannon located at 60^o and facing the equator will be moving east at 800 km/hr. When its shell is fired towards the equator, the shell will be moving east at 800 km/hr, but as it approaches the equator it will be moving over land that is traveling east *faster* than the projectile. So the projectile gets "behind" its target, and will land to the west of its destination. But from the point of view of the cannon facing the equator, the path of the shell still appears to have been deflected to the right (green arrow, Figure 8.2.2). Therefore, in the Northern Hemisphere, the apparent Coriolis deflection will *always* be to the **right**.

In the Southern Hemisphere the situation is reversed (Figure 8.2.2). Objects moving towards the equator from the south pole are moving from low speed to high speed, so are left behind and their path is deflected to the left. Movement from the equator towards the south pole also leads to deflection to the left. In the Southern Hemisphere, the Coriolis deflection is always to the **left** from the point of origin.

The magnitude of the Coriolis deflection is related to the difference in rotation speed between the start and end points. Between the poles and 60^o latitude, the difference in rotation speed is 800 km/hr. Between the equator and 30^o latitude, the difference is only 200 km/hr (Figure 8.2.2). Therefore the strength of the Coriolis Effect is stronger near the poles, and weaker at the equator.

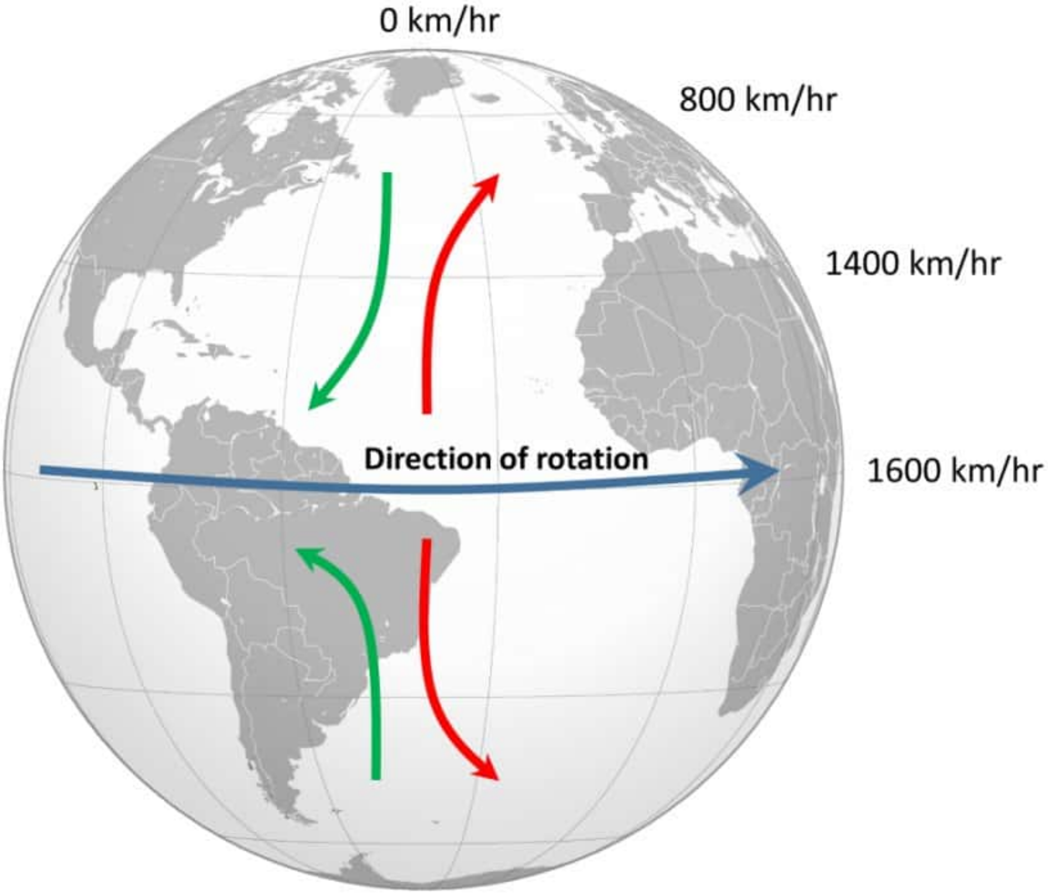


Figure 8.2.2 The Coriolis Effect. Objects moving from the equator towards the poles (red arrows) move into a region of slower rotational speed and their paths are deflected "ahead" of their point of origin. Movement from high latitudes to low latitudes (green arrows) goes from a region of low speed to a region of higher rotation speed, and there is deflection "behind" their point of origin. In the Northern Hemisphere this deflection is always to the right from the point of origin, and in the Southern Hemisphere the deflection is always to the left (Modified by PW from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).

Because of the rotation of the Earth and the Coriolis Effect, rather than a single atmospheric convection cell in each hemisphere, there are three major cells per hemisphere. Warm air rising at the equator cools as it moves through the upper atmosphere, and it descends at around 30° latitude. The convection cells created by rising air at the equator and sinking air at 30° are referred to as **Hadley Cells**, of which there is one in each hemisphere. The cold air that descends at the poles moves over the Earth's surface towards the equator, and by about 60° latitude it begins to rise, creating a **Polar Cell** between 60° and 90°. Between 30° and 60° lie the **Ferrel Cells**, composed of sinking air at 30° and rising air at 60° (Figure 8.2.3). With three convection cells in each hemisphere that rotate in alternate directions, the surface winds no longer always blow from the poles towards the equator as in the non-rotating Earth in Figure 8.2.1. Instead, surface winds in both hemispheres blow towards the equator between 90° and 60° latitude, and between 0° and 30° latitude. Between 30° and 60° latitude, the surface winds blow towards the poles (Figure 8.2.3).

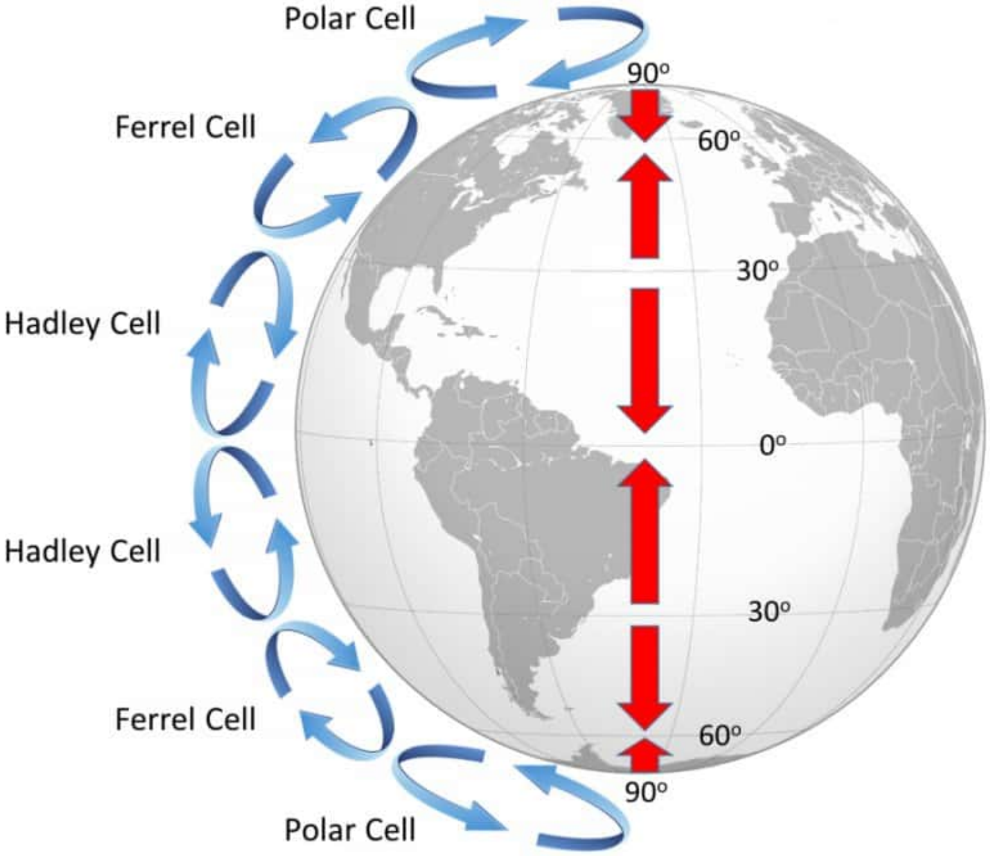


Figure 8.2.3 *On a rotating Earth, there are three atmospheric convection cells in each hemisphere, leading to alternating bands of surface winds (red arrows) (Modified by PW from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).*

The surface winds created by the atmospheric convection cells are also influenced by the Coriolis Effect as they change latitudes. The Coriolis Effect deflects the path of the winds to the right in the Northern Hemisphere and to the left in the Southern Hemisphere. Adding this deflection leads to the pattern of prevailing winds illustrated in Figure 8.2.4. Between the equator and 30° latitude are the **trade winds**; the northeast trade winds in the Northern Hemisphere and the southeast trade winds in the Southern Hemisphere (note that winds are named based on the direction from which they originate, not where they are going). The **westerlies** are the dominant winds between 30° and 60° in both hemispheres, and the **polar easterlies** are found between 60° and the poles.

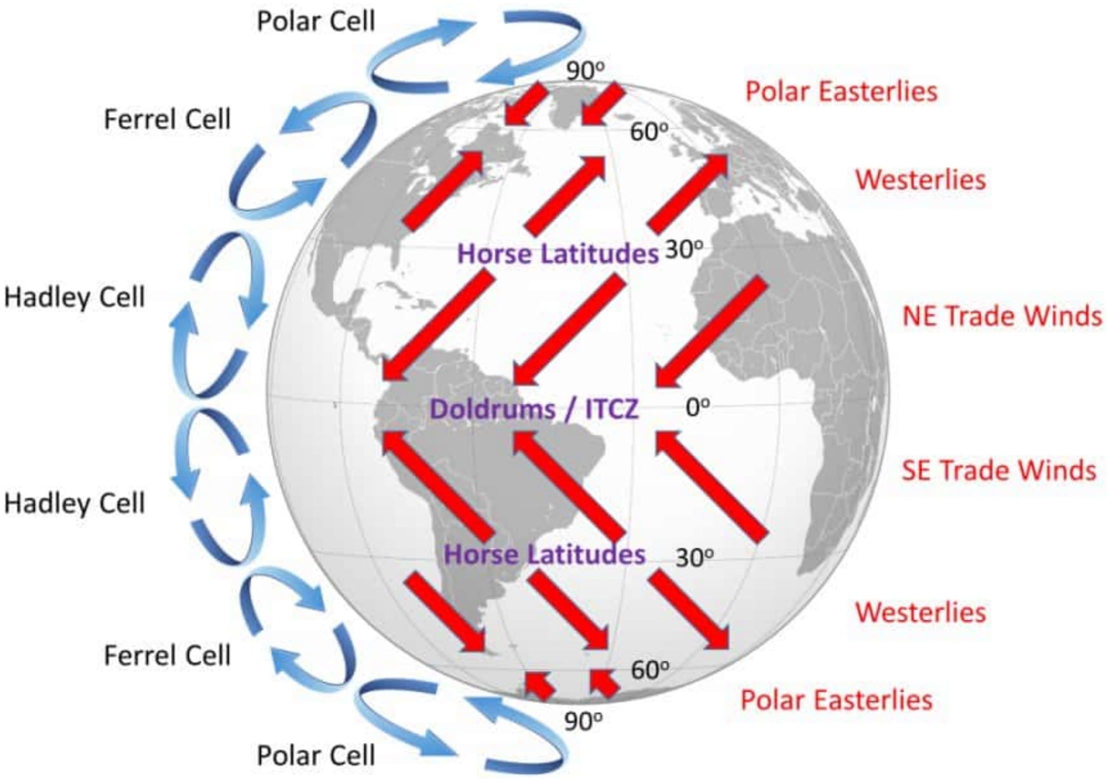


Figure 8.2.4 *The prevailing wind patterns of Earth (Modified by PW from globe image by Location_of_Cape_Verde_in_the_globe.svg: Eddo derivative work: Luan fala! [CC BY-SA 3.0], via Wikimedia Commons).*

In between these wind bands lie regions of high and low pressure. High pressure zones occur where air is descending, while low pressure zones indicate rising air. Along the equator the rising air creates a low pressure region called the **doldrums**, or the **Intertropical Convergence Zone** (ITCZ)(convergence zone because this is where the trade winds converge). At 30° latitude there are high pressure zones of descending air known as the **horse latitudes**, or the subtropical highs. Finally, at 60° lies another low pressure region called the **polar front**. It should be noted that these high and low pressure zones are not fixed in place; their latitude fluctuates depending on the season, and these fluctuations have important implications for regional climates.

Doldrums? Horse latitudes? Trade winds?

These may seem like some odd names for these atmospheric phenomena, but many of them can be traced back to maritime traditions and lore.

The **doldrums** refer to regions of low pressure around the equator. In these areas, air is rising rather than moving horizontally, so these regions commonly encounter very light winds. The lack of wind could leave sailing ships becalmed for days or weeks at a time, which was not good for the morale of the ship's crew.

Like the doldrums the **horse latitudes** are also areas with light winds, this time due to descending air, which could leave ships becalmed. One explanation for the term "horse latitudes" is that when these ships became stranded they ran the risk of running out of food or water. To conserve these resources, sailors would throw their dead or dying horses overboard, hence the "horse latitudes." Another explanation is that many sailors received part of their pay before a voyage, and often spent it before departing. This meant that they would spend the first part of the voyage working without pay and in debt, a period called the "dead horse" time, which might last for a few months. When they started earning their pay once again, they had a "dead horse" ceremony and threw a pretend horse overboard. The timing of this ceremony often coincided with reaching the horse latitudes, leading to the association of the ceremony with the location. A third explanation is that a ship was referred to as "horsed" when winds were weak and the ship instead had to rely on ocean currents to move them. This could be a common occurrence in the high pressure zones around 30° latitude, so they were referred to as the horse latitudes.

The term **trade winds** may have originally derived from the terms for "track" or "path", but the term may have become more common during European exploration and commercialization of the New World. Mariners sailing from Europe to the New World could sail south until they reached the trade winds, which would then propel their ships across the Atlantic to the Caribbean. To return to Europe, ships could sail to the northeast until they entered the westerlies, which would then steer them back to Europe.

8.3 Winds and Climate

In the previous section we learned that rising air creates low pressure systems, and sinking air creates high pressure. In addition to their role in creating the surface winds, these high and low pressure systems also influence other climatic phenomena. Along the equator air is rising as it is warmed by solar radiation (section 8.2). Warm air contains more water vapor than cold air, which is why we experience humidity during the summer and not during the winter. The water content of air roughly doubles with every 10° C increase in temperature. So the air rising at the equator is warm and full of water vapor; as it rises into the upper atmosphere it cools, and the cool air can no longer hold as much water vapor, so the water condenses and forms rain. Therefore, low pressure systems are associated with precipitation, and we see wet habitats like tropical rainforests near the equator (Figure 8.3.1).

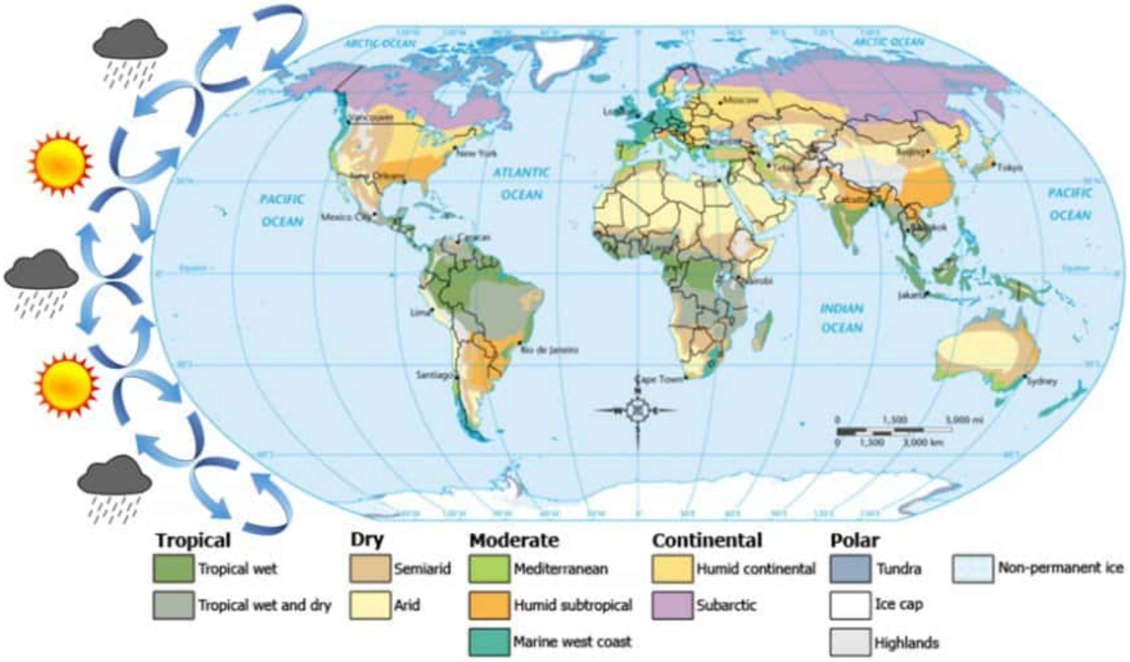


Figure 8.3.1 *Major global climatic regions in relation to atmospheric convection cells. Rising air and low pressure creates rain and wet environments at 0° and 60° latitudes, while high pressure, sinking air creates drier conditions at 30° and 90° latitudes. (Modified by PW; Map by Waitak at en.wikipedia Later version(s) were uploaded by Splette at en.wikipedia; Sun by Inductiveload (Own work Based on File:Nuvola_apps_kweather.svg); Raincloud by Calusarul (Own work); all [CC BY-SA 3.0], via Wikimedia Commons).*

After rising and producing rain near the equator, the air masses move towards 30° latitude and sink back towards Earth as part of the Hadley convection cells. This air has lost most of its moisture after producing the equatorial rains, so the sinking air is dry, resulting in arid climates near 30° latitude in both hemispheres. Many of the major desert regions on Earth are located near 30° latitude, including much of Australia, the Middle East, and the Sahara Desert of Africa (Figure 8.3.1). The air also becomes compressed and heats up as it sinks, absorbing any moisture from the clouds and creating clear skies. Thus high pressure systems are associated with dry weather and clear skies. This cycle of high and low pressure regions continues with the Ferrel and Polar convection cells, leading to rain and the boreal forests at 60° latitude in the Northern Hemisphere (there are no corresponding large land masses at these latitudes in the Southern Hemisphere). At the poles, descending, dry air produces little precipitation, leading to the polar desert climate.

The elevation of the land also plays a role in precipitation and climactic characteristics. As moist air moves over land and encounters mountains it rises, expands, and cools because of the declining pressure and temperature. The cool air holds less water vapor, so condensation occurs and rain falls on the windward side of the mountains. As the air passes over the mountains to the leeward side, it is now dry air, and as it sinks the pressure increases, it heats back up, any moisture revaporizes, and it creates dry, deserts regions behind the mountains (Figure 8.3.2). This phenomenon is referred to as a **rain shadow**, and can be found in areas such as the Tibetan Plateau and Gobi Desert behind the Himalayas, Death Valley behind the Sierra Nevada mountains, and the dry San Joaquin Valley in California.

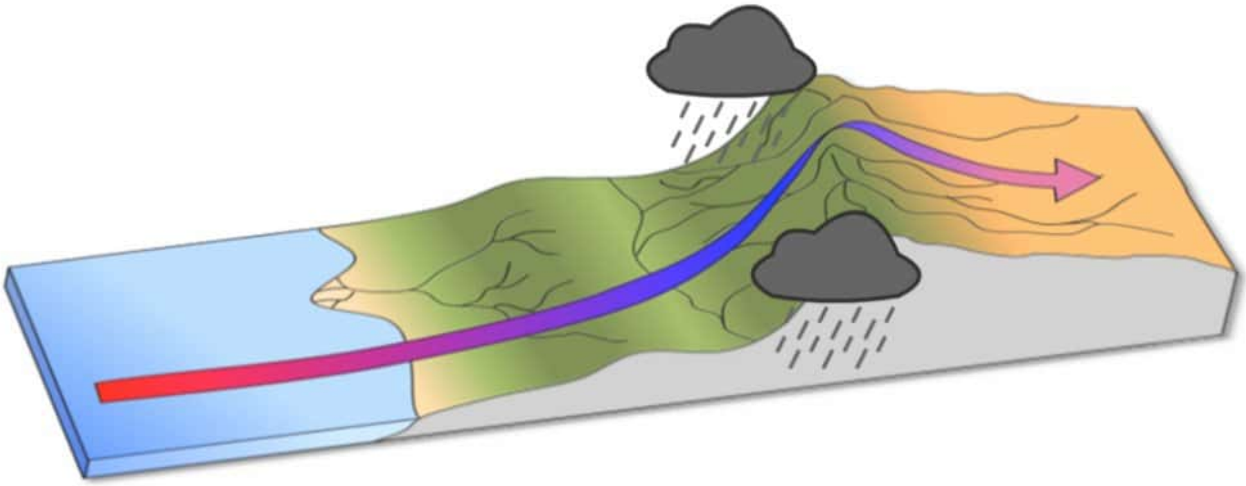


Figure 8.3.2 *A rain shadow. Air rising over mountains cools and condenses and forms rain, leaving dry descending air and arid conditions on the other side of the mountain (Modified by PW from Thebiologyprimer, Public domain via Wikimedia Commons).*

Rising and falling air are also responsible for more localized, short-term wind patterns in coastal areas. Due to the high heat capacity of water, land heats up and cools down about five times faster than water. During the day the sun heats up the land faster than it heats the water, setting up a convection cell of warmer rising air over the land and sinking cooler air over the water. This creates winds blowing from the water towards the land during the day and early evening; a **sea breeze** (Figure 8.3.3). The opposite occurs at night, when the land cools more quickly than the ocean. Now the ocean is warmer than the land, so air rises over the water and sinks over the land, creating a convection cell where winds blow from land towards the water. This is a **land breeze**, which blows at night and into the early morning (Figure 8.3.3).

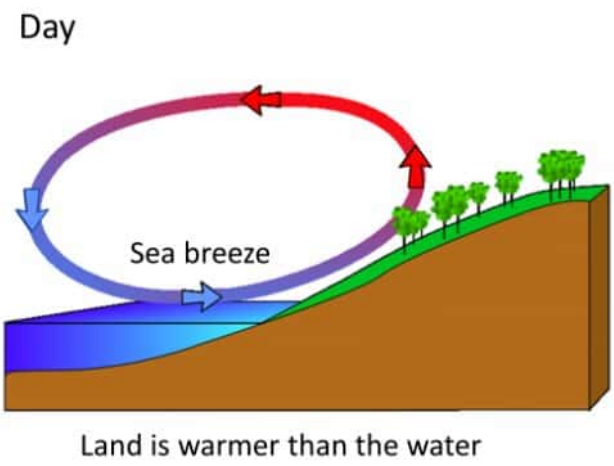


Figure 8.3.3 *Land heats and cools faster than the ocean, so during the day the land is warmer than the water leading to rising air over land and a sea breeze. At night, the ocean is warmer than the land, creating a land breeze (Modified by PW derivative work: Ingwik (Diagrama de formacion de la brisa-breeze.png) [CC-BY-SA-3.0 or GFDL (http://www.gnu.org/copyleft/fdl.html)], via Wikimedia Commons).*

The same phenomenon leads to seasonal climatic changes in many areas. During the winter the lower pressure is over the warmer ocean, and the high pressure is over the colder land, so winds blow from land to sea. In summer the land is warmer than the ocean, causing low pressure over the land and winds to blow from the ocean towards the land. The winds blowing from the ocean contain a lot of water vapor, and as the moist air passes over land and rises, it cools and condenses causing seasonal rains, such as the summer **monsoons** of southeast Asia (Figure 8.3.4).

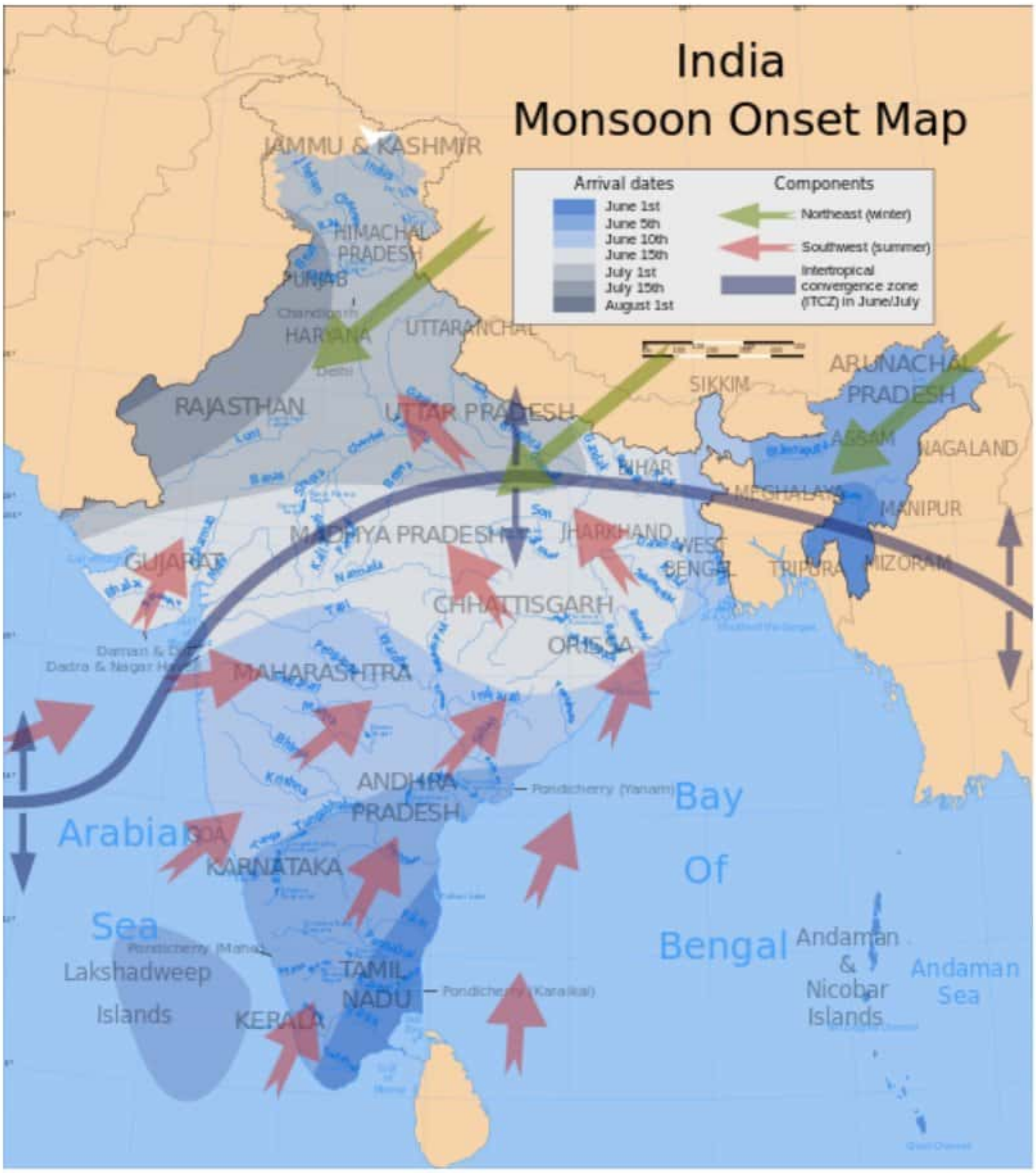


Figure 8.3.4 Seasonal wind patterns and monsoons over India. In summer, moist air from the ocean moves over the continent and rises, creating rain and the summer monsoons (pink arrows). In winter, winds are blowing from land to the sea, leading to the dry season (green arrows) (By Saravask, based on work by Planemad and Nichalp [CC BY-SA 3.0], via Wikimedia Commons).

8.4 Hurricanes

The most dramatic examples of low pressure systems leading to storms and rain are hurricanes, cyclones, and typhoons. All three of these terms describe the same atmospheric processes and the same types of storms; it's just that different terminology is used in different parts of the world. In the Atlantic and Northeast Pacific, the storms are called hurricanes, in the Indian and South Pacific Oceans they are referred to as cyclones, and they are called typhoons in the Northwest Pacific.

Hurricanes begin as low pressure systems formed over warm, tropical water. They only form in tropical regions because they need the heat from the warm water to fuel the storm. The warm, moist air rises, cools, and condenses, forming rain, and the condensation releases more latent heat into the atmosphere. This heat causes even more air to rise and condense, further fueling the storm.

As the air rises towards the center of the storm, more warm tropical air rushes in to replace it, causing very strong winds. But the air does not move directly towards the center of the storm. Because of the large size of hurricanes, the air rushing towards the center will be deflected by the Coriolis Effect, causing the entire storm to rotate. In the Northern Hemisphere that deflection is to the right, causing Northern Hemisphere hurricanes to rotate counterclockwise. In the Southern Hemisphere, the winds are deflected to the left, leading to a clockwise rotation (Figure 8.4.1).

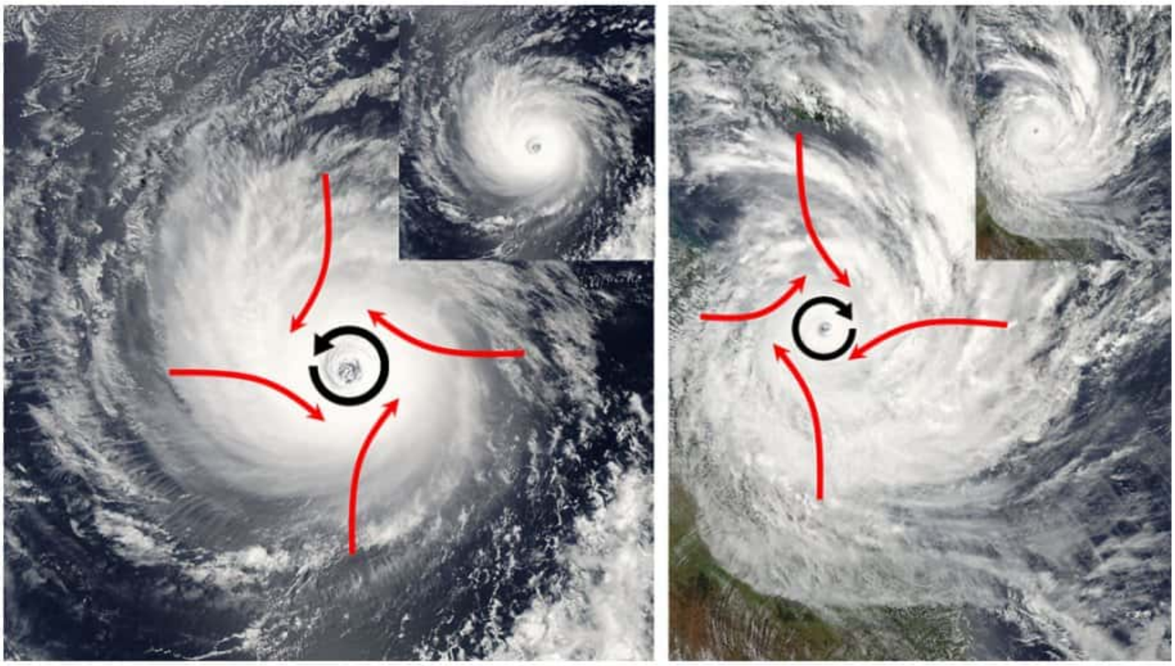


Figure 8.4.1 *Hurricanes in the Northern Hemisphere rotate counterclockwise (left, Hurricane Daniel, 2006), as air rushes towards the center and is deflected to the right by the Coriolis Effect. In the Southern Hemisphere, hurricanes rotate clockwise as the Coriolis deflection is to the left (right, Cyclone Yasi, 2011) (Modified by PW; Daniel image by NASA image courtesy Jeff Schmaltz, MODIS Land Rapid Response Team at NASA GSFC; Yasi image by NASA; MODIS [Public domain], via Wikimedia Commons).*

The violent winds characteristic of hurricanes are the result of the spiraling air that is moving towards the center of the storm, and once its winds exceed 74 mph the storm officially becomes a hurricane. At the very center of the hurricane, the pressure is so low that cool, dry air from the upper atmosphere get sucked downwards, leading to a central region of calm, clear skies; the hurricane's eye (Figure 8.4.2).

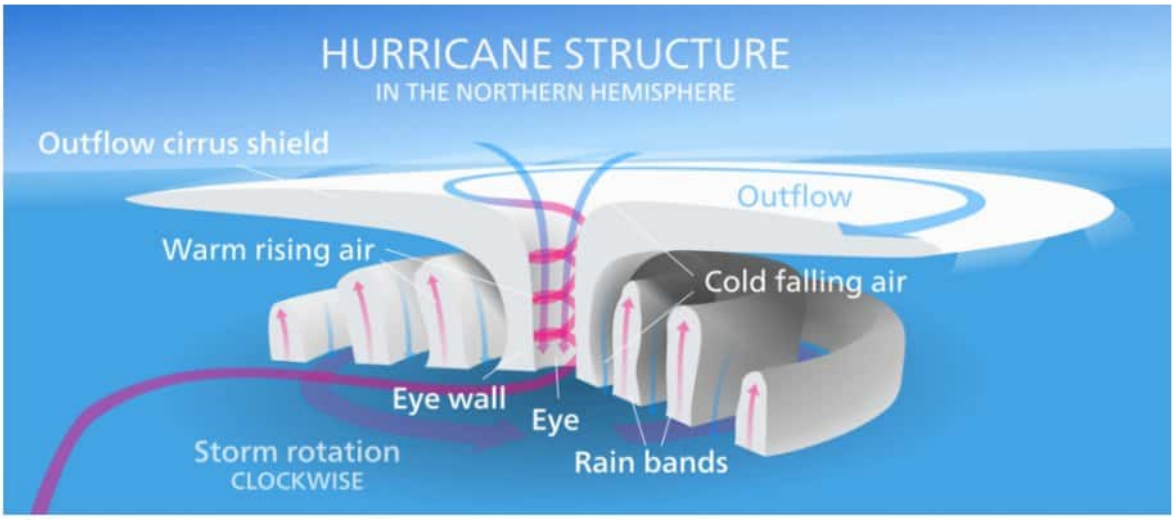


Figure 8.4.2 *Hurricane structure. Air rising in the center of the hurricane is replaced by warm air moving inwards, and the Coriolis Effect deflects the winds, causing the storm to rotate. In the eye, the extreme low pressure causes cool, dry air to sink, creating calm, clear conditions within the eye (By Kelvinsong (Own work) [CC BY 3.0], via Wikimedia Commons).*

Hurricanes in the North Atlantic form as tropical storms over the warm water off of the African coast, and are moved east to west by the trade winds (Figure 8.4.3). As the storms move west over the tropical ocean, their energy increases until they reach hurricane status. As they approach the Caribbean, the Coriolis Effect deflects their path to the right, causing them to move towards the north (Figure 8.4.3). Eventually hurricanes might make landfall, causing extensive damage to coastal areas through the high winds, rain, and flooding. However, hurricanes often die out fairly soon after reaching land. When a storm moves over land it becomes cut off from the warm moist ocean air that has sustained it. Without that fuel source, the storm loses power and begins to dissipate.

Figure 8.4.3 *Hurricane tracks in the North Atlantic from 1980-2005. Hurricanes begin near the coast of Africa and are blown westward by the trade winds. Coriolis deflection causes them to take a northward path as they approach the Caribbean (By Nilfanion [Public domain], via Wikimedia Commons).*

A similar pattern occurs in the Pacific and in the Southern Hemisphere. The trade winds move the storms from east to west, and they are deflected as they approach the coasts; to the right in the Northern Hemisphere and to the left in the Southern Hemisphere (Figure 8.4.4).

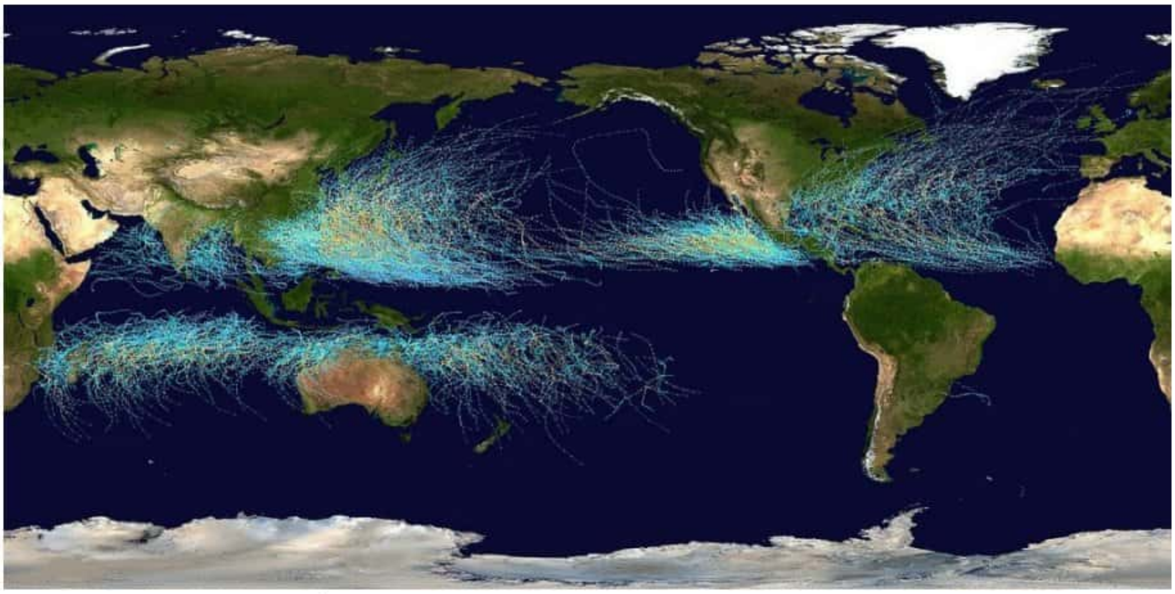


Figure 8.4.4 *Global hurricane/cyclone tracks 1985-2005. Hurricanes move west via the trade winds, and their paths are deflected away from the equator in both hemispheres as they approach the continents (Background image: NASA this version: Nilfanion [Public domain], via Wikimedia Commons).*

While the very high winds and intense rain of hurricanes can cause significant damage, in many cases it is the **storm surge** that leads to the most death and destruction. The storm surge is a “hill” of water that forms on the ocean surface below a hurricane. The surge is the result of two processes; a small hill is produced due to the extreme low pressure in the eye of a hurricane, which pulls water upwards towards the eye, creating a pressure surge. A larger surge is produced by the winds blowing and piling up water in the direction the storm is traveling (Figure 8.4.5). As the hurricane makes landfall, the effect of the storm surge is equivalent to a very large and sudden rise in sea level as the surge moves over the land, causing extensive flooding.

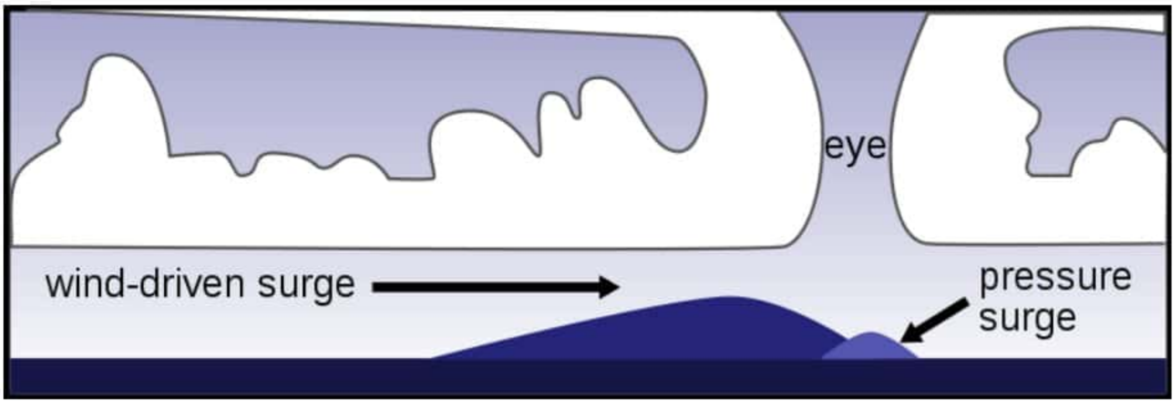


Figure 8.4.5 *Storm surges are created by hurricanes and move with the storm, causing a rapid rise in sea level when they reach shore. Pressure surges are due to the low pressure within the hurricane's eye, wind-driven surges are a product of high winds piling up water (By Howcheng. Original graphic by Robert Simmon, NASA GSFC. [Public domain], via Wikimedia Commons).*

In 1970 the Bhola Cyclone struck Bangladesh with a 40 ft. storm surge, leading to the death of about 500,000 people, the deadliest hurricane in history. The east coast of the United States was hit by the New England Hurricane of 1938, which had a 16 ft. storm surge and left almost 700 people dead.

Preventing Storm Surge Damage

In response to the hurricane-related tragedies like those listed above, may cities have built hurricane barriers designed to reduce the flooding and damage associated with storm surges. Downtown Providence, Rhode Island, USA, was submerged under 13 feet of water during the Great New England hurricane of 1938, and was flooded again following Hurricane Carol in 1954. In the 1960s the Fox Point Hurricane Barrier was constructed at the mouth of the Providence River. It consists of a high wall with three “doors” that are left open under normal conditions, but can be closed during a hurricane to prevent a storm surge of up to 20.5 feet from inundating the city (Figure 8.4.6, left). A related concept is seen in the storm surge barrier on the Hollandse IJssel river in the Netherlands, where the barrier is lowered to prevent flooding (Figure 8.4.6, right).

Figure 8.4.6 *The Fox Point Hurricane Barrier in Providence, RI, USA (left) and the surge barrier on the Hollandse IJssel river in southern Holland. (Fox Point by Marcbela (Marc N. Belanger) (Own work) [Public domain], via Wikimedia Commons; Dutch barrier by Mark Voorendt (Own work) [CC BY-SA 4.0], via Wikimedia Commons).*

8.5 Climate Change

*Modified from "Physical Geology" by Steven Earle**

If one thing has been constant about Earth's climate over geological time, it is its constant change. In the geological record, we can see this in the evidence of glaciations in the distant past, and we can also detect periods of extreme warmth by looking at the isotope composition of seafloor sediments. Not only has the climate changed frequently, the temperature fluctuations have been very significant. Today's mean global temperature is about 15°C. However, during its coldest periods, the global mean was as cold as -50°C, while at various times during the Paleozoic and Mesozoic and during the Paleocene–Eocene thermal maximum, it was close to 30°C.

There are two parts to climate change, the first one is known as **climate forcing**, which is when conditions change to give the climate a little nudge in one direction or the other. The second part of climate change, and the one that typically does most of the work, is what we call a **feedback**. When a climate forcing changes the climate a little, a whole series of environmental changes take place, many of which either exaggerate the initial change (**positive feedback**), or suppress the change (**negative feedback**).

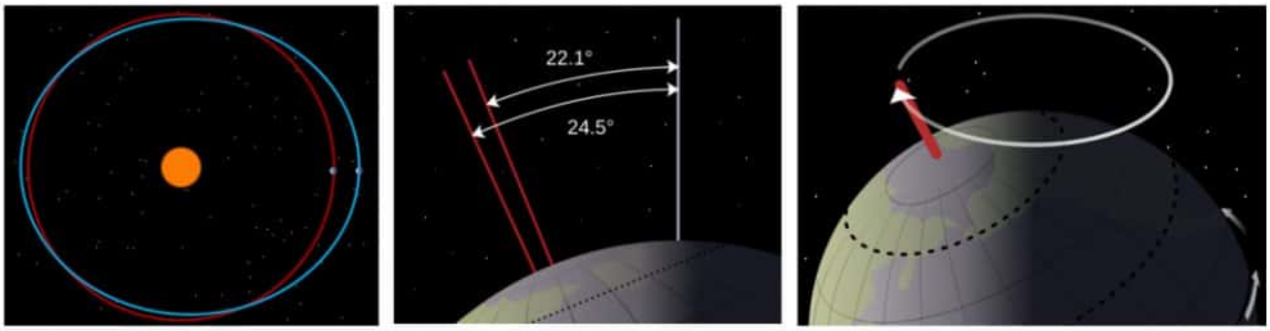
An example of a climate forcing mechanism is the increase in the amount of carbon dioxide (CO_2) in the atmosphere that results from our use of fossil fuels. CO_2 traps heat in the atmosphere and leads to climate warming. Warming changes vegetation patterns; contributes to the melting of snow, ice, and permafrost; causes sea level to rise; reduces the solubility of CO_2 in sea water; and has a number of other minor effects. Most of these changes contribute to more warming. Melting of permafrost, for example, is a strong positive feedback because frozen soil contains trapped organic matter that is converted to CO_2 and methane (CH_4) when the soil thaws. Both these gases accumulate in the atmosphere and add to the warming effect. On the other hand, if warming causes more vegetation growth, that vegetation should absorb CO_2, thus reducing the warming effect, which would be a negative feedback. Under our current conditions — a planet that still has lots of glacial ice and permafrost — most of the feedbacks that result from a warming climate are positive feedbacks and so the climate changes that we cause get naturally amplified by natural processes.

Natural Climate Forcing

Natural climate forcing has been going on throughout geological time. A wide range of processes has been operating at widely different time scales, from a few years to billions of years. The longest-term natural forcing variation is related to the evolution of the Sun. Like most other stars of a similar mass, our Sun is evolving. For the past 4.6 billion years, its rate of nuclear fusion has been increasing, and it is now emitting about 40% more energy (as light) than it did at the beginning of geological time. A difference of 40% is big, so it's a little surprising that the temperature on Earth has remained at a reasonable and habitable temperature for all of this time. The mechanism for that relative climate stability has been the evolution of our atmosphere from one that was dominated by CO_2, and also had significant levels of CH_4 — both greenhouse gasses — to one with only a few hundred parts per million of CO_2 and just under 1 part per million of CH_4. Those changes to our atmosphere have been no accident; over geological time, life and its metabolic processes have evolved (such as the evolution of photosynthetic bacteria that consume CO_2) and changed the atmosphere to conditions that remained cool enough to be habitable.

The position of the Earth relative to the Sun is another important component of natural climate forcing. Earth's orbit around the Sun is nearly circular, but like all physical systems, it has natural oscillations. First, the shape of the orbit changes on a regular time scale (close to 100,000 years) from being close to circular to being very slightly elliptical. But the circularity of the orbit is not what matters; it is the fact that as the orbit becomes more elliptical, the position of the Sun within that ellipse becomes less central or more **eccentric** (Figure 8.5.1a).

Eccentricity is important because when it is high, the Earth-Sun distance varies more from season to season than it does when eccentricity is low.



(a) The 100,000 year cycle of eccentricity of the Sun within the Earth's orbit. The blue orbit is more elliptical than the red one, and the Sun is offset from the centre of the ellipse

(b) The 41,000 year cycle of the angle of tilt (obliquity) of the Earth's axis (red lines) compared to a line perpendicular to the plane of the Earth's orbit (light blue line).

(c) the 20,000 year cycle of precession of the Earth's rotational axis

Figure 8.5.1 *Components of the Milankovitch cycles, which influence global climate over thousands of years (Steven Earle, "Physical Geology").*

Second, Earth rotates around an axis through the North and South Poles, and that axis is at an angle to the plane of Earth's orbit around the Sun (Figure 8.5.1b). The angle of tilt (also known as **obliquity**) varies on a time scale of 41,000 years. When the angle is at its maximum (24.5°), Earth's seasonal differences are accentuated. When the angle is at its minimum (22.1°), seasonal differences are minimized. The current hypothesis is that glaciation is favored at low seasonal differences as summers would be cooler and snow would be less likely to melt and more likely to accumulate from year to year. Third, the direction in which Earth's rotational axis points also varies, on a time scale of about 20,000 years (Figure 8.5.1c). This variation, known as **precession**, means that although the North Pole is presently pointing to the star Polaris (the pole star), in 10,000 years it will point to the star Vega. The importance of eccentricity, tilt, and precession to Earth's climate cycles (now known as **Milankovitch Cycles**) was first pointed out by Yugoslavian engineer and mathematician Milutin Milankovitch in the early 1900s. Milankovitch recognized that although the variations in the orbital cycles did not affect the total amount of insolation (light energy from the Sun) that Earth received, it did affect where on Earth that energy was strongest.

Volcanic eruptions don't just involve lava flows and exploding rock fragments; various particulates and gases are also released, the important ones being sulphur dioxide and CO_2. Sulphur dioxide is an aerosol that reflects incoming solar radiation and has a net cooling effect that is short lived (a few years in most cases, as the particulates settle out of the atmosphere within a couple of years), and doesn't typically contribute to longer-term climate change. Volcanic CO_2 emissions can contribute to climate warming but only if a greater-than-average level of volcanism is sustained over a long time (at least tens of thousands of years). It is widely believed that the catastrophic end-Permian extinction (at 250 Ma) resulted from warming initiated by the eruption of the massive Siberian Traps over a period of at least a million years.

Ocean currents are important to climate, and currents also have a tendency to oscillate. Glacial ice cores show clear evidence of changes in the Gulf Stream that affected global climate on a time scale of about 1,500 years during the last glaciation. The east-west changes in sea-surface temperature and surface pressure in the equatorial Pacific Ocean, known as the El Niño Southern Oscillation or ENSO (see section 9.6) varies on a much shorter time scale of between two and seven years. These variations tend to garner the attention of the public because they have significant climate implications in many parts of the world. The strongest El Niños in recent decades were in 1983, 1998, and 2015 and those were very warm years from a global perspective. During a strong El Niño, the equatorial Pacific sea-surface temperatures are warmer than normal and heat the atmosphere above the ocean, which leads to warmer-than-average global temperatures.

Climate Feedbacks

As already stated, climate feedbacks are critically important in amplifying weak climate forcings into full-blown climate changes. Since Earth still has a very large volume of ice, mostly in the continental ice sheets of Antarctica and Greenland, but also in alpine glaciers and permafrost, melting is one of the key feedback mechanisms. Melting of ice and snow leads to several different types of feedbacks, an important one being a change in albedo, or the reflectivity of a surface. Earth's various surfaces have widely differing albedos, expressed as the percentage of light that reflects off a given material. This is important because most solar energy that hits a very reflective surface is not absorbed and therefore does little to warm Earth. Water in the oceans or on a lake is one of the darkest surfaces, reflecting less than 10% of the incident light, while clouds and snow or ice are among the brightest surfaces, reflecting 70% to 90% of the incident light. When sea ice melts, as it has done in the Arctic Ocean at a disturbing rate over the past decade, the albedo of the area affected changes dramatically, from around 80% down to less than 10%. Much more solar energy is absorbed by the water than by the pre-existing ice, and the temperature increase is amplified. The same applies to ice and snow on land, but the difference in albedo is not as great. When ice and snow on land melt, sea level rises. (Sea level is also rising because the oceans are warming and that increases their volume; see section 13.7). A higher sea level means a larger proportion of the planet is covered with water, and since water has a lower albedo than land, more heat is absorbed and the temperature goes up a little more. Since the last glaciation, sea-level rise has been about 125 m; a huge area that used to be land is now flooded by heat-absorbent seawater. During the current period of anthropogenic climate change, sea level has risen only about 20 cm, and although that doesn't make a big change to albedo, sea-level rise is accelerating.

Most of northern Canada, Alaska, Russia, and Scandinavia has a layer of permafrost that ranges from a few centimeters to hundreds of meters in thickness. Permafrost is a mixture of soil and ice and it also contains a significant amount of trapped organic carbon that is released as CO_2 and CH_4 when the permafrost breaks down. Because the amount of carbon stored in permafrost is in the same order of magnitude as the amount released by burning fossil fuels, this is a feedback mechanism that has the potential to equal or surpass the forcing that has unleashed it. In some polar regions, including northern Canada, permafrost includes methane hydrate, a highly concentrated form of CH_4 trapped in solid form. Breakdown of permafrost releases this CH_4. Even larger reserves of methane hydrate exist on the seafloor, and while it would take significant warming of ocean water down to a depth of hundreds of meters, this too is likely to happen in the future if we don't limit our impact on the climate. There is strong isotopic evidence that the Paleocene–Eocene thermal maximum was caused, at least in part, by a massive release of sea-floor methane hydrate.

There is about 45 times as much carbon in the ocean (as dissolved bicarbonate ions, HCO_3^-) as there is in the atmosphere (as CO_2), and there is a steady exchange of carbon between the two reservoirs (see section 5.5). But the solubility of CO_2 in water decreases as the temperature goes up. In other words, the warmer it gets, the more oceanic bicarbonate that gets transferred to the atmosphere as CO_2. That makes CO_2 solubility another positive feedback mechanism. Vegetation growth responds positively to both increased temperatures and elevated CO_2 levels, and so in general, it represents a negative feedback to climate change because the more the vegetation grows, the more CO_2 is taken from the atmosphere. But it's not quite that simple, because when trees grow bigger and more vigorously, forests become darker (they have lower albedo) so they absorb more heat. Furthermore, climate warming isn't necessarily good for vegetation growth; some areas have become too hot, too dry, or even too wet to support the plant community that was growing there, and it might take centuries for something to replace it successfully. All of these positive (and negative) feedbacks work both ways. For example, during climate cooling, growth of glaciers leads to higher albedos, and formation of permafrost results in storage of carbon that would otherwise have returned quickly to the atmosphere.

Anthropogenic Climate Change

When we talk about anthropogenic climate change, we are generally thinking of the industrial era, which really got going when we started using fossil fuels (coal to begin with, and later oil and natural gas) to drive machinery and trains, and to generate electricity. That was around the middle of the 18th century. The issue with fossil fuels is that they involve burning carbon that was naturally stored in the crust over hundreds of millions of years as part of Earth's process of counteracting the warming Sun.

A rapidly rising population, the escalating level of industrialization and mechanization of our lives, and an increasing dependence on fossil fuels have driven the anthropogenic climate change of the past century. The trend of mean global temperatures since 1880 is shown in Figure 8.5.2. For approximately the past 55 years, the temperature has increased at a relatively steady and disturbingly rapid rate, especially compared to past changes. The average temperature now is approximately 0.8°C higher than before industrialization, and two-thirds of this warming has occurred since 1975.

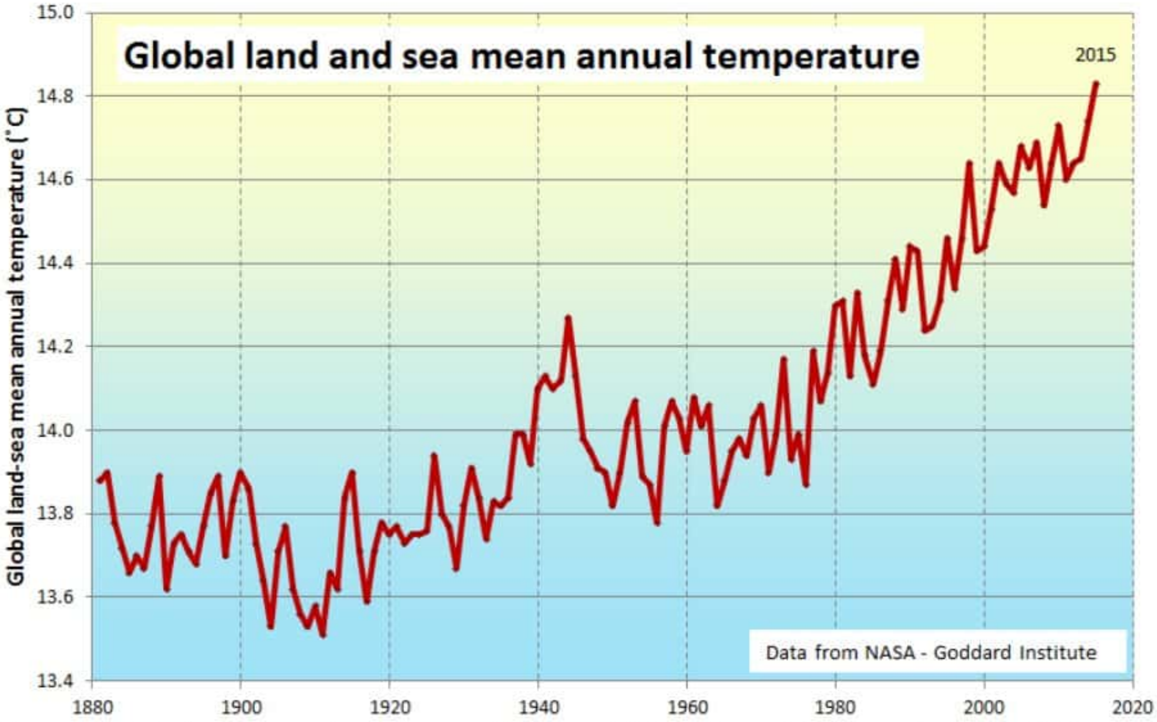


Figure 8.5.2 *Global mean annual temperatures for the period from 1880 to 2015 (Steven Earle, "Physical Geology", by SE from data at NASA at: http://data.giss.nasa.gov/gistemp/tabledata_v3/GLB.Ts+dSST.txt).*

The Intergovernmental Panel on Climate Change (IPCC), established by the United Nations in 1988, is responsible for reviewing the scientific literature on climate change and issuing periodic reports on several topics, including the scientific basis for understanding climate change, our vulnerability to observed and predicted climate changes, and what we can do to limit climate change and minimize its impacts. Figure 8.5.3, from the fifth report of the IPCC, issued in 2014, shows the relative contributions of various greenhouse gases and other factors to current climate forcing, based on the changes from levels that existed in 1750.

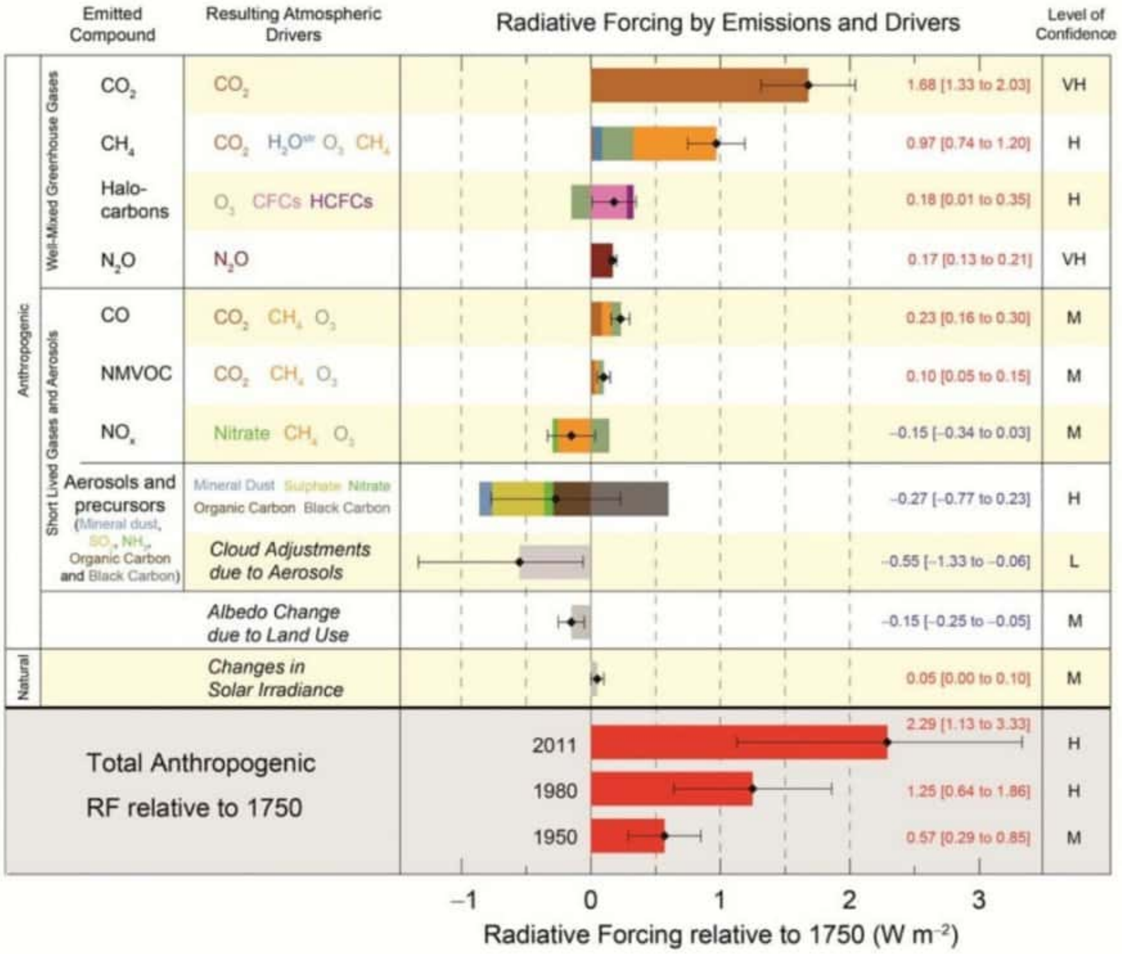


Figure 8.5.3 *The relative importance of factors that are contributing to anthropogenic warming (from http://www.ipcc.ch/report/graphics/index.php?t=Assessment%20Reports&r=AR5%20-%20WG1&f=SPM).*

The biggest anthropogenic contributor to warming is the emission of CO_2, which accounts for 50% of positive forcing. CH_4 and its atmospheric derivatives (CO_2, H_2O, and O_3) account for 29%, and the halocarbon gases (mostly leaked from air-conditioning appliances) and nitrous oxide (N_2O) (from burning fossils fuels) account for 5% each. Carbon monoxide (CO) (also produced by burning fossil fuels) accounts for 7%, and the volatile organic compounds other than methane (NMVOC) account for 3%. CO_2 emissions come mostly from coal- and gas-fired power stations, motorized vehicles (cars, trucks, and aircraft), and industrial operations (e.g., smelting), and indirectly from forestry. CH_4 emissions come from production of fossil fuels (escape from coal mining and from gas and oil production), livestock farming (mostly beef), landfills, and wetland rice farming. N_2O and CO come mostly from the combustion of fossil fuels. In summary, close to 70% of our current greenhouse gas emissions come from fossil fuel production and use, while most of the rest comes from agriculture and landfills. Figure 8.5.4 shows the IPCC's projections for temperature increases over the next 100 years as a result of these increasing greenhouse gases.

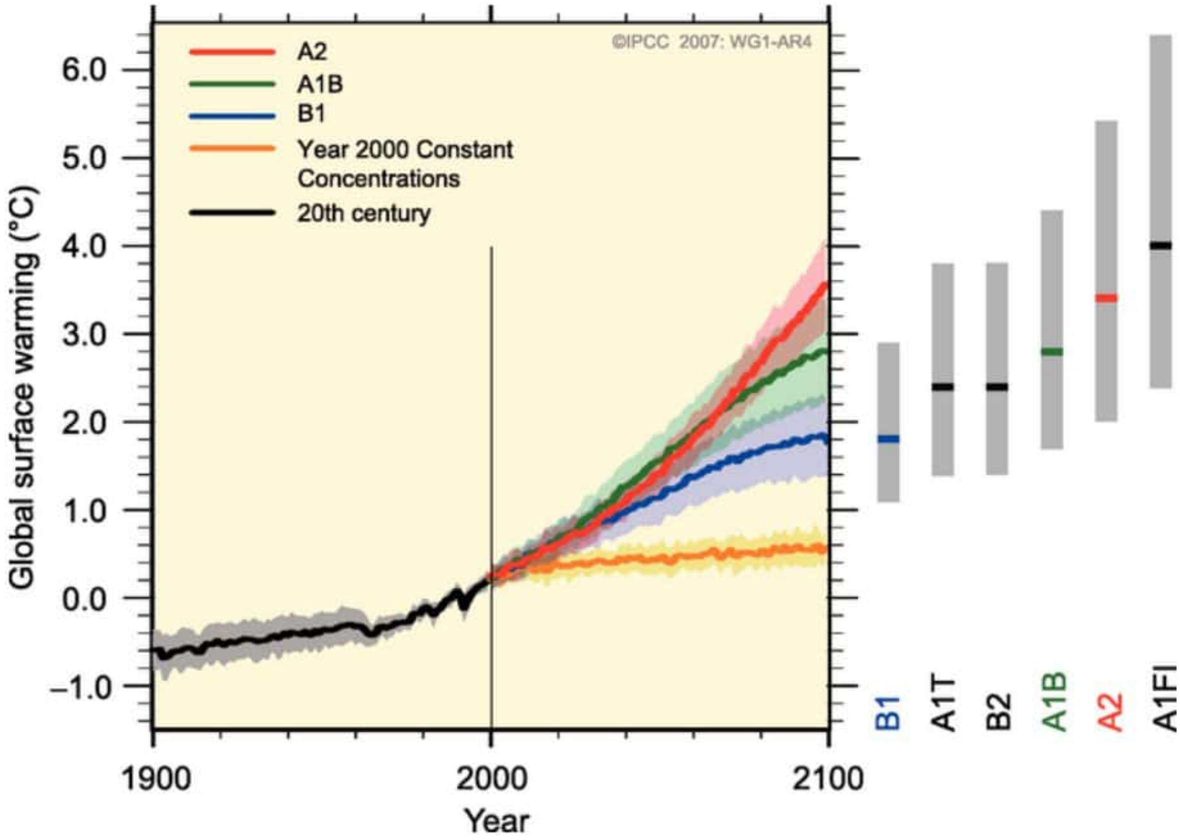


Figure 8.5.4 Projected global temperature increases for the 21st century based on a range of different IPCC scenarios of future political and technological variables (from https://www.ipcc.ch/publications_and_data/ar4/wg1/en/fig/figure-spm-5-l.png).

Impacts of Climate Change

We've all experienced the effects of climate change over the past decade. However, it's not straightforward for climatologists to make the connection between a warming climate and specific weather events, and most are justifiably reluctant to ascribe any specific event to climate change. In this respect, the best measures of climate change are those that we can detect over several decades, such as the temperature changes shown in Figure 8.5.2, or the sea level rise shown in Figure 8.5.5. As already stated, sea level has risen approximately 20 cm since 1750, and that rise is attributed to both warming (and therefore expanding) seawater and melting glaciers and other land-based snow and ice (melting of sea ice does not contribute directly to sea level rise as it is already floating in the ocean, see section 13.7).

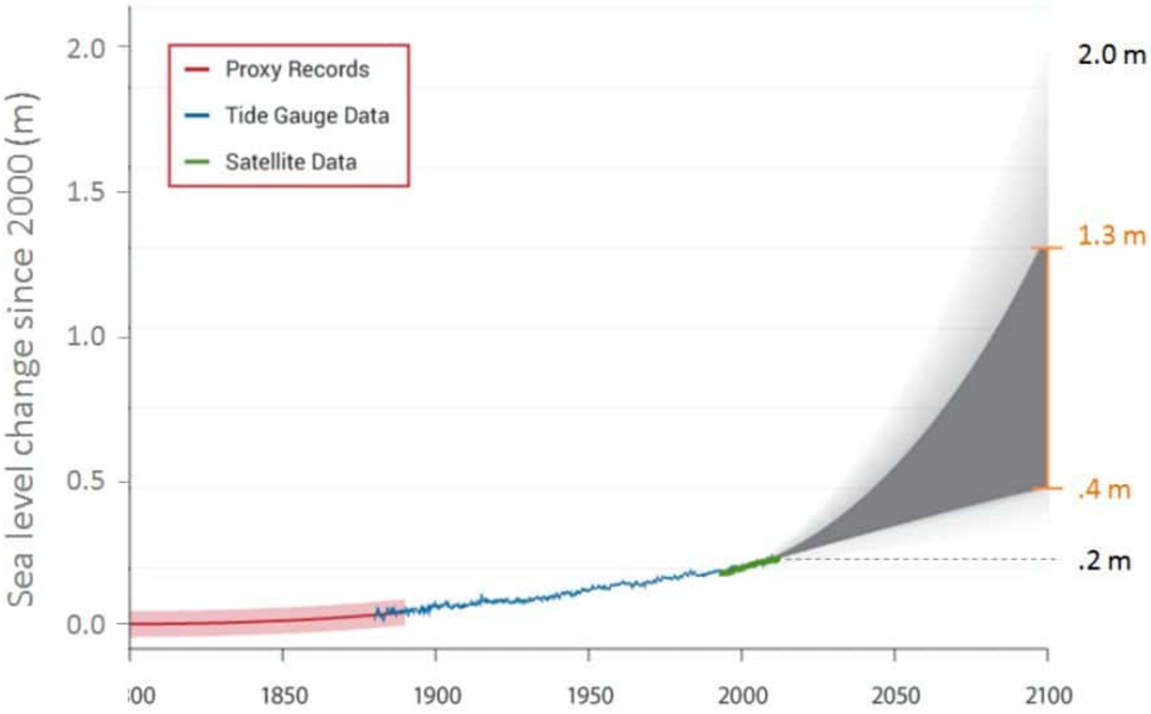


Figure 8.5.5 *Projected sea-level increases to 2100, showing likely range (grey) and possible maximum (Stephen Earle, "Physical Geology", adapted by SE from: http://nca2014.globalchange.gov/report/our-changing-climate/sea-level-rise#intro-section-2 based on data in Parris et al., 2012, NOAA).*

Projections for sea level rise to the end of this century vary widely. This is in large part because we do not know which of the above climate change scenarios (Figure 8.5.4) we will most closely follow, but many are in the range from 0.5 m to 2.0 m. One of the problems in predicting sea level rise is that we do not have a strong understanding of how large ice sheets, such as Greenland and Antarctica, will respond to future warming. Another issue is that the oceans don't respond immediately to warming. For example, with the current amount of warming, we are already committed to a future sea level rise of between 1.3 m and 1.9 m, even if we could stop climate change today. This is because it takes decades to centuries for the existing warming of the atmosphere to be transmitted to depth within the oceans and to exert its full impact on large glaciers. Most of that committed rise would take place over the next century, but some would be delayed longer. And for every decade that the current rates of climate change continue, that number increases by another 0.3 m. In other words, if we don't make changes quickly, by the end of this century we'll be locked into 3 m of future sea level rise. In a 2008 report, the Organization for Economic Co-operation and Development (OECD) estimated that by 2070 approximately 150 million people living in coastal areas could be at risk of flooding due to the combined effects of sea level rise, increased storm intensity, and land subsidence. The assets at risk (buildings, roads, bridges, ports, etc.) are in the order of $35 trillion ($35,000,000,000,000). Countries with the greatest exposure of population to flooding are China, India, Bangladesh, Vietnam, U.S.A., Japan, and Thailand. Some of the major cities at risk include Shanghai, Guangzhou, Mumbai, Kolkata, Dhaka, Ho Chi Minh City, Tokyo, Miami, and New York.

One of the other risks for coastal populations, besides sea level rise, is that climate warming is also associated with an increase in the intensity of tropical storms (e.g., hurricanes or typhoons; see section 8.4), which almost always bring serious flooding from intense rain and storm surges. Some recent examples are New Orleans in 2005 with Hurricane Katrina, and New Jersey and New York in 2012 with Hurricane Sandy. Tropical storms get their energy from the evaporation of warm seawater in tropical regions. In the Atlantic Ocean, this takes place between 8° and 20° N in the summer. Figure 8.5.6 shows the variations in the sea-surface temperature (SST) of the tropical Atlantic Ocean (in blue) versus the amount of power represented by Atlantic hurricanes between 1950 and 2008 (in red). Not only has the overall intensity of Atlantic hurricanes increased with the warming since 1975, but the correlation between hurricanes and sea-surface temperatures is very strong over that time period.

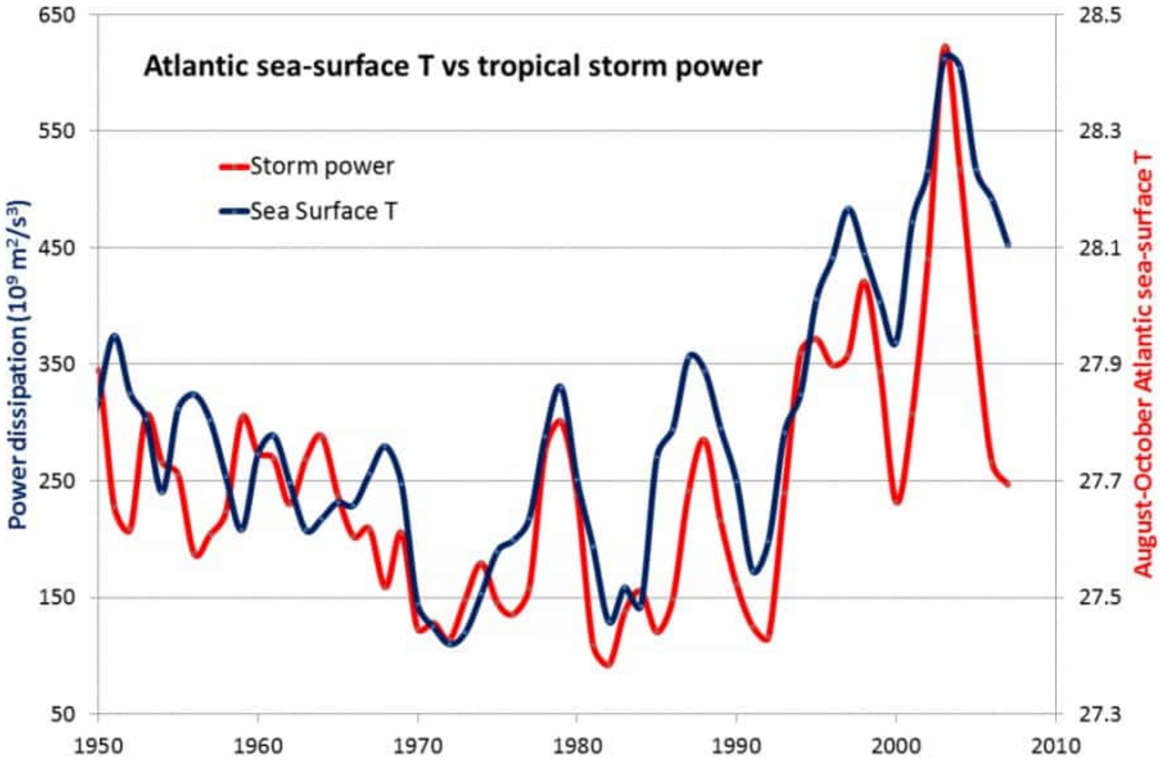
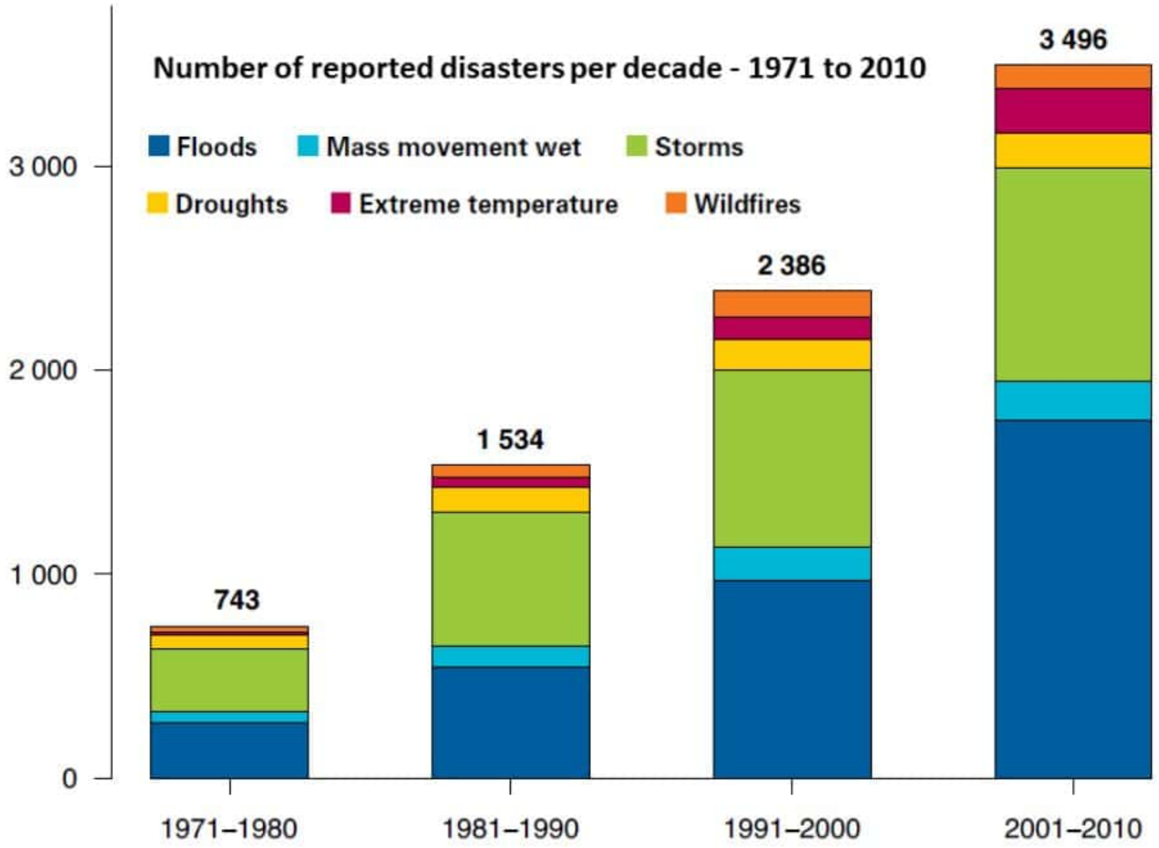


Figure 8.5.6 *Relationship between Atlantic tropical storm cumulative annual intensity and Atlantic sea-surface temperatures (Steven Earle, "Physical Geology", by SE from data at: http://wind.mit.edu/~emanuel/Papers_data_graphics.htm).*

The geographical ranges of diseases and pests, especially those caused or transmitted by insects, have been shown to extend toward temperate regions because of climate change. West Nile virus and Lyme disease are two examples that already directly affect North Americans, while dengue fever could be an issue in the future (dengue became a "nationally notifiable condition" in the United States in 2010). For several weeks in July and August of 2010, a massive heat wave affected western Russia, especially the area southeast of Moscow, and scientists have stated that climate change was a contributing factor. Temperatures soared to over 40°C, as much as 12°C above normal over a wide area, and wildfires raged in many parts of the country. Over 55,000 deaths are attributed to the heat and to respiratory problems associated with the fires. A summary of the impacts of climate change on natural disasters is given in Figure 8.5.7. The major types of disasters related to climate are floods and storms, but the health implications of extreme temperatures are also becoming a great concern. In the decade 1971 to 1980, extreme temperatures were the fifth most common natural disasters; by 2001 to 2010, they were the third most common.



World Meteorological Association - Atlas of Mortality and Economic Losses from Weather, Climate and Water Extremes - 2014

Figure 8.5.7 *Numbers of various types of disasters between 1971 and 2010 (From WMO atlas of mortality and economic Losses from weather, climate and water extremes, 2014).*
